THE EXTRAGALACTIC ORIGIN OF THE ARCTURUS GROUP

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ABSTRACT

We reanalyze the group of stars associated kinematically with Arcturus (Eggen 1971), and confirm that they constitute a peculiar grouping of metal-poor stars with similar apocentric radius, common angular momentum, and distinct metal abundance patterns. These properties are consistent with those expected for a group of stars originating from the debris of a disrupted satellite. The Arcturus group stands out clearly in the catalog of Beers et al. (2000) as well as in other compilations of metal-poor stars in the solar neighborhood. Its angular momentum appears too low to arise from dynamical perturbations induced by the Galactic bar, and coincides with that of the kinematically-peculiar population of stars identified above and below the Galactic plane by Gilmore, Wyse & Norris (2002): the Arcturus group is in all likelihood the solar neighborhood extension of such population. Further analysis is needed to confirm our proposal that Arcturus, together with some of the brightest stars in the night sky, may have formed beyond the confines of the Galaxy. However, validating the extragalactic origin of the Arcturus group would lend support to the prevalence of accretion events envisioned in hierarchical models of galaxy formation, and would suggest that early mergers may have contributed a substantial fraction of the old and metal-deficient stars in the Galactic disk.

Subject headings: Galaxy: disk, structure, formation

1. INTRODUCTION

The discovery of substructure in the distribution of stars in the outer regions of galaxies like the Milky Way and M31 constitutes indisputable evidence that accretion events and mergers have played a role in building up their stellar halos (Ibata et al. 1994, Helmi et al. 1999, Majewski et al. 2003). Although the role of such events in the formation of the Galactic disk components is not yet fully understood, models of the thick disk component typically envision the tidal heating of an extant thin disk by a merging satellite (Quinn & Goodman 1986). Recent numerical simulations of disk galaxy formation also suggest that disrupted satellites might have contributed a significant fraction of the old stars in the disk of the Galaxy (Abadi et al. 2003a,b). As with the stellar halo, long-lived traces of such events may be preserved in the form of substructure in the orbital distribution of stars in the disk (Helmi et al 2003).

Identifying such debris ought to be easier in samples where contamination by the thin disk component is minimized, such as samples of metal poor/old stars, or else samples collected *in situ* away from the disk or far from the Galactic center. The discovery of a "ring" of stars of almost certain extragalactic origin in the outer disk of the Milky Way by the SDSS (Newberg et al 2002, Yanny et al 2003), as well as recent report of a galaxy being cannibalized in the Milky Way disk (Martin et al 2003) provide examples that this process indeed seems to be at work in

the Galaxy (Helmi et al 2003, Rocha-Pinto et al 2003).

Gilmore, Wyse & Norris (2002) have also recently argued for substructure in the Galactic thick disk. They postulate the existence of a distinct population of stars, with kinematics intermediate between the canonical thick disk and the stellar halo (mean rotational velocity of $\sim 100 \, \mathrm{km \, s^{-1}}$) to explain the results of their spectroscopic survey of F–G stars located 0.5–5 kpc away from the Galactic plane.

Substructure in the disk has been noted since the early days of Galactic structure research (see, e.g., Eggen 1998 and references therein), and has usually been interpreted as signature of the gradual dissolution of loosely bound star clusters in the clumpy potential of the disk. One example is the group of stars associated by Eggen (1971) with the bright star Arcturus, whose rotation speed lags the Local Standard of Rest (LSR) by roughly $\sim 100 \, \mathrm{km \, s^{-1}}$. We discuss below that evidence for a population of stars with rotation speeds lagging the LSR by $\sim 100 \, \mathrm{km \, s^{-1}}$ is also present in the metal-poor star catalog of Beers et al (2000; hereafter B00), and in the compilation of Gratton et al (2003, hereafter GCCLB).

In this *Letter* we reassess the status of Eggen's Arcturus group by using modern distance, proper motions, radial velocities, and metallicity determinations available in the literature. We argue that the Arcturus group; the structure in the B00 and GCCLB compilations; as well as the kinematically-odd population of stars discovered by Gilmore, Wyse & Norris (2002), are all part of the same, dynamically coherent group of stars that might have originated in the disruption of a fairly massive satellite early during the Galaxy's assembly.

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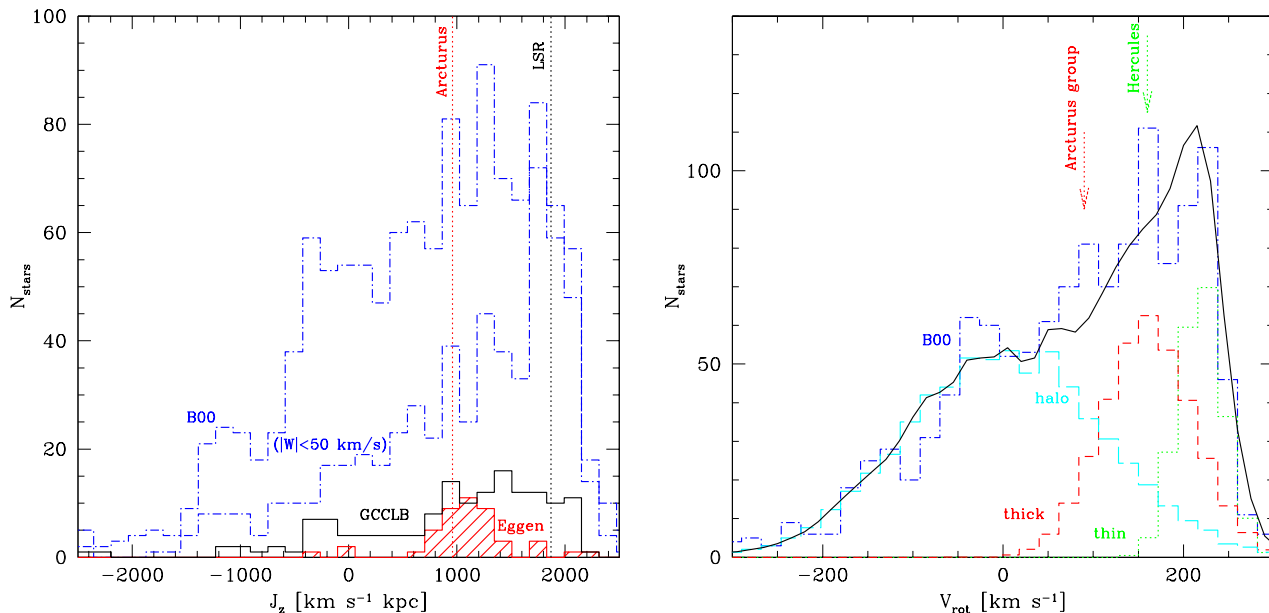
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FIG. 1.— Panel (a) shows the angular momentum distribution of stars in the B00 catalog (top dot-dashed histogram); those in the Arcturus group candidate list of Eggen (1996; 1998; shaded histogram at the bottom); and stars in the compilation of Gratton et al. (2003; solid histogram). The middle dot-dashed histogram correspond to all B00 stars on "disk-like" orbits, i.e., $|W| < 50$ kms s^{-1}. There is evidence in all these samples (which favor metal-poor stars) for an "excess" of stars with angular momentum coincident with the Arcturus group at $J_z \sim 950$ km s^{-1} kpc. Panel (b) shows the rotational velocity distribution of all stars in the B00 catalog, decomposed into three canonical Galactic (Gaussian) components: halo, thick disk, and thin disk. The solid curve denotes the sum of all three components. Note the "excess" of stars lagging the LSR rotation by ~ 120 km s^{-1}, coincident with the Arcturus group. See text for full details.

2. THE ARCTURUS GROUP

2.1. Eggen's stars

Over the years, Eggen compiled a list of stars kinematically similar to Arcturus from catalogs of nearby stars with large proper motions (Eggen 1971a; 1987; 1996; 1998). Distances to some of these stars, however, were unavailable at the time, and Eggen would *assign* them distances so that they had negligible velocity dispersion in V ($\sigma_V \sim 0.5$ km s^{-1}), [3] as required by his interpretation. This somewhat arbitrary step has made Eggen's interpretation controversial but, remarkably, his choice led most candidates to lie along relatively narrow isochrones, enabling Eggen to derive ages for these stars. He concluded that most Arcturus group members are old ($\tau \gtrsim 10$ Gyrs) and metal poor ([Fe/H]~ -0.6; Griffin & Lynas-Gray, 1999).

The shaded histogram (labelled "Eggen") in Fig. 1a shows the distribution of the vertical component of the angular momentum, J_z, for stars listed by Eggen (1996, 1998) as members of the Arcturus group. We have included here only stars with available proper motions and Hipparcos parallaxes. This effectively restricts Eggen's sample to 46 stars within a sphere of radius ~ 300 pc centered on the Sun. The dispersion in J_z (corresponding to a dispersion in V of $\sigma_V \sim 50$ km s^{-1}) is much larger than demanded by Eggen's interpretation of this association as a dissolving star cluster. Still, many of the candidates are indeed on

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[3] We use U, V, and W to denote radial, tangential and vertical velocities in Galactic coordinates, measured relative to the LSR. U is positive outwards, V in the direction of the Sun's rotation, and W towards the North Galactic Pole. We assume that the Sun's (U,V,W) velocity is $(-9,12,7)$ km s^{-1}.

orbits that lag the Sun's rotation speed by ~ 100 km s^{-1}. Furthermore, many of these stars are on disk-like orbits; $\sim 70\%$ of them have vertical speeds that do not exceed 50 km s^{-1} and do not climb farther than ~ 1 kpc out of the Galactic plane. These stars show no obvious net motion in the radial direction.

2.2. Metal-deficient stars in the solar neighborhood

B00 provide a catalog of metal-deficient stars compiled with the specific aim of minimizing kinematic selection biases. This is the largest sample of metal-poor ([Fe/H] ≤ -0.6) stars with available abundances, distances, and radial velocities. Proper motions are also available for many of these stars, making it a good sample to search for substructure in the orbits of metal-deficient stars (see, e.g., Chiba & Beers 2000; Brook et al. 2003).

The top dot-dashed histogram in Fig. 1a shows the angular momentum distribution for all stars in the B00 sample. The full sample is dominated by the canonical "thick disk" component, whose J_z distribution peaks at ~ 1300 km s^{-1} kpc, and lags the LSR rotation speed by 50–60 km s^{-1}. The halo component contributes a significant number of counter-rotating stars, and is fairly prominent in this sample biased towards metal-poor stars.

The B00 distribution shows a number of prominent features that persist even when the sample is restricted to stars with disk-like kinematics ($|W| \leq 50$ km s^{-1}, see the lower dot-dashed histogram in Fig. 1a). We shall focus on two of these features, also seen in the distribution of rotation-speeds shown in Fig. 1b ($V_{\rm rot} = J_z/R$, where R is the polar radial distance measured in the meridional plane).

The first feature, coincident with the peak velocity expected for the canonical thick disk, likely signals the "Hercules" stream (Eggen 1971b). This stream has $V \sim -60$ km s^{-1} and $U \sim 35$ km s^{-1} (Skuljan et al. 1999), and is thought to originate from dynamical resonances induced by the Galactic bar (Dehnen 2000, Fux 2001). Intriguingly, the second feature, at $J_z \sim 950$ km s^{-1} kpc, has an angular momentum similar to that of Arcturus. The same feature is also seen in the GCCLB compilation of nearby metal-poor stars (see solid histogram in Figure 1a).

The statistical significance of this feature is difficult to assess, since the sample is subject to a number of subtle and complex biases and selection effects. We can nevertheless estimate it roughly by comparing the actual number of stars with velocities similar to that of Arcturus, with that expected for a random sample drawn from the standard Galactic components: thin disk, thick disk and stellar halo. This is shown in Fig. 1b, where the $V_{\rm rot}$ distribution has been decomposed into three Gaussians. From left to right, the halo, thick disk, and thin disk components are assumed to have $(\bar{V}_{\rm rot}, \sigma)$ equal to (0,110), (160,50) and (220,25) km s^{-1}, respectively.

The halo distribution is normalized to match the number of counter-rotating stars, whereas the relative contributions of the thick and thin disks are chosen to match the $V_{\rm rot}$ distribution of the remaining co-rotating stars. The fit obtained is shown by the thick solid curve in Fig. 1b. Most random realizations are unable to account for the "excess" of stars labelled "Arcturus group"; only 16 out of 1000 realizations give a number of stars comparable to what is observed. Such odds seem compelling enough to warrant exploring further the provenance of stars with such peculiar kinematics.

2.3. The origin of the Arcturus group

Could the Arcturus group be the result of perturbations to the orbits of disk stars induced by the Galactic bar? As discussed above, detailed modeling of such perturbations have linked stellar groupings in phase space to orbital resonances in a rotating barred potential (see, e.g., Dehnen 2000, Fux 2001). However, these perturbations typically induce small velocity changes ($\sim$ 20–50 km s^{-1}), and therefore are unlikely to be responsible for the 110–130 km s^{-1} lag of stars in the Arcturus group. Moreover, such perturbations tend to produce a net mean radial velocity with respect to the LSR, which is not observed neither for the B00 candidates nor for stars in the original Eggen's compilation (see Fig. 2).

2.3.1. The group as tidal debris

A compelling alternative is that Arcturus is part of the tidal debris of a disrupted satellite, akin to the interpretation of the SDSS "ring" proposed by Helmi et al (2003). Intriguingly, the angular momentum of Arcturus is roughly half of that of a circular orbit at the solar circle, reminiscent of the dynamics of the SDSS "ring". A further similarity with the outer Galactic "ring" is the lack of net radial motion, which suggests that these structures have become recognizable as stars of similar energy crowd at the apocenter of their orbits. As discussed below, an extragalactic origin for the Arcturus group would explain its
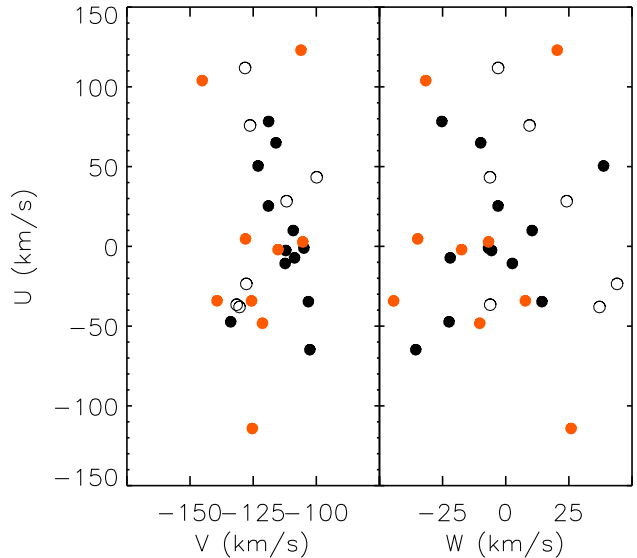

FIG. 2.— Velocity components of candidate stars in the Arcturus group, from Eggen's (black) and GCCLB (gray/red) compilations. Stars are selected as candidates if $|V_{\rm rot} - V_{\rm Arct}| \le 20$ km s^{-1} and $|W| \le 50$ km s^{-1}. Open circles show the velocities of particles in the simulations located in a small volume around the "Sun", 8 Gyr after infall.

sizeable velocity dispersion, as well as its vertical extension and distinct metal abundance.

We can test the plausibility of this scenario by following the disruption of a small satellite with orbit similar to that of Arcturus in the potential of the Galaxy. To this aim, we have integrated Arcturus' orbit 8 Gyrs back in time and use those orbital parameters to release a 10^8 M$_\odot$ satellite (modelled with 10^5 particles after a King sphere with core and tidal radius 233 pc and 1.57 kpc, respectively). The numerical simulations include the self-gravity of the satellite using a quadrupole expansion of the internal potential (Zaritsky & White 1988), but are otherwise run in a fixed Galactic potential, of the form given by Johnston et al. (1996). We shall focus on particles ("stars") located in a small volume around the Solar neighborhood, 5 to 8 Gyr after the satellite is disrupted.

The open circles in Fig. 2 show the velocities of particles located within 500 pc of the "Sun" (assumed to be at 8.5 kpc from the center of the Galaxy, and on the Galactic plane), which should be compared to stream candidates taken from the Eggen (solid black circles) and GCCLB (solid gray/red circles) samples. The good agreement between the mean velocities of the candidate stars and particles in the simulation indicate that the dynamics of the stream is consistent with that expected for the debris of a shredded satellite. Clues to the original mass of the satellite are preserved in the velocity dispersion of the group, but will depend on the number of streams expected to run through the solar neighbourhood at present. This is very hard to ascertain given current uncertainties in the velocities.

2.3.2. Chemical properties of the Arcturus group

Supporting evidence for the "shredded-satellite" interpretation may be found in the chemical properties of stars in the Arcturus group. The Beers et al (2000) catalog

lists [Fe/H] estimates for all stars, and further examination shows that stars with angular momentum consistent with the Arcturus group span a wide range of metallicities, roughly $-2.5 <$[Fe/H]< -0.5. Does this broad metallicity distribution argue against Eggen's suggestion that these stars are part of a disrupting cluster born out of the same molecular cloud ? It is indeed clear that most of the B00 stars in the appropriate J_z range are metal-poor, but we would expect to find a significant contamination from halo and metal-poor thick disk stars in this range of J_z (c.f. Fig 1b).

On the other hand, the tightness of the [α/Fe] relation for the group candidates in Fig. 3, compared with the non-group candidates, does suggest a common brief star formation history for the stars in this range of J_z. This is best shown using the GCCLB dataset, which includes abundance estimates for elements other than Fe. This dataset may thus be used to search for potential features in the chemical properties of group candidate stars. In Figure 3, open symbols are used for all stars in the GCCLB sample, whilst filled circles are used for Arcturus group candidates; i.e., stars with J_z in the range $(700, 1100)$ km s^{-1} kpc, and $|W| < 50$ km s^{-1}. Candidate stars of the group define a tight sequence in the [α/Fe]–[Fe/H] plane, much tighter than expected for stars of similar [Fe/H] selected at random from the full GCCLB sample.

Interestingly, the group candidates appear to follow, with minimal scatter, a well defined enrichment pattern roughly consistent with simple self-enrichment models, where the overabundance in [α/Fe] (relative to solar) suggests a gas consumption timescale short compared with that of supernova type Ia ignition. The curve in Fig. 3 shows the predictions of Matteucci & Francois (1989) for a one-zone model[4] that self-enriches to [Fe/H]$= -1$ in about 1 Gyr, before the Fe-rich yield of SNIa start to play a role, leading to a sudden change in the slope of the curve. The good agreement between the model prediction and the candidate stars should be taken as a demonstration of the plausibility of our interpretation rather than as an endorsement of this particular model; other choices of model parameters may lead to similarly good fits, although all are likely to require a short timescale for enrichment.

We conclude that the coherence in the dynamical and chemical properties of stars in the group suggest that they originate from a single satellite system that was dragged and shredded into the disk of the Galaxy early during its assembly.

3. SUMMARY AND DISCUSSION

The peculiar angular momentum of the Arcturus group, together with its moderate velocity dispersion and singular metal abundance, all point to a possible extragalactic origin for the group. Age estimates are available for some stars in the group (Fuhrmann 2000, 2003), and suggest that it is perhaps as old as 10-12 Gyr. This would imply that the group is the debris from an ancient accretion event.

This accretion event has probably contributed a significant number of metal-deficient stars to the solar neighborhood, as shown by the prominence of the group in

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[4] The curve corresponds to [Si/Fe] vs [Fe/H] in their model 1. Results are similar for other α elements.
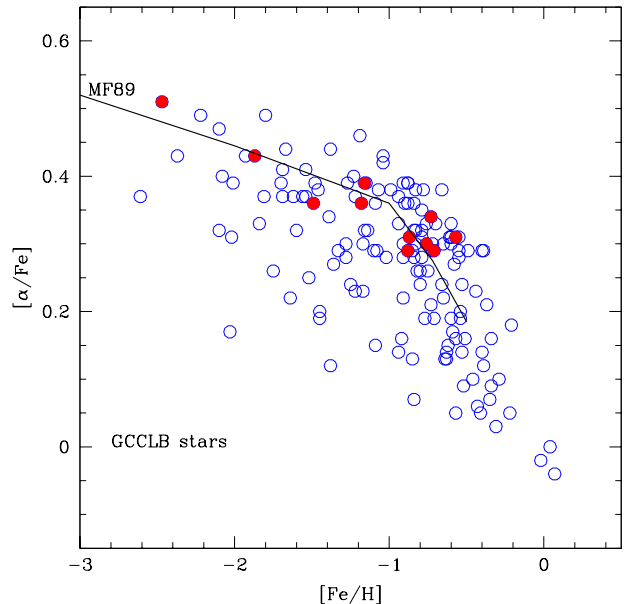

FIG. 3.— Abundance ratios for stars in the GCCLB sample. Open circles correspond to all stars in each sample, whereas filled circles indicate candidate stars of the Arcturus group. Note that these stars delineate a well define sequence in the abundance ratios that may be interpreted as resulting from a short episode of star formation where a system self-enriched to a metallicity of order one-third solar. The curve correspond to model 1 of Matteucci & Francois (1989). See text for further details.

samples that favor metal-deficient stars. The presence of this dynamically-coherent group may explain some of the variance in the results of dynamical studies of the thick disk. Indeed, some of these studies have concluded that the bulk of the thick disk lags the LSR by only ~ 30–50 km s^{-1} (Beers & Sommer-Larsen 1995, Ojha et al 1996, Norris 1999), whereas others have favored a lag of ~ 100 km s^{-1} instead (Wyse & Gilmore 1986, Chen et al 2000, Fuhrmann 2000, 2003), possibly reflecting the different contribution of stars in the group to each sample.

There are a number of inquiries that may further validate (or refute) our interpretation. For example, confirming the link between the Arcturus group and the debris identified by Gilmore, Wyse & Norris outside the plane would help to uphold the group's extragalactic origin. Most of the stars in the Arcturus group are located close to their orbital apocenter, where density enhancements are expected: we may have detected a "shell" similar to those observed around elliptical galaxies (Helmi et al 2003). Other distinct features of this shell interpretation would include a rapid decline in the importance of the group at increasingly large Galactocentric distance (shells are "sharp") and, of course, the presence of other shells at different Galactocentric radii. It may also be possible to find other members of the progenitor of the Arcturus group by searching for stars on disk-like eccentric orbits with metal abundances consistent with the "sequence" outlined by the group in Figure 3.

Finally, it is oddly gratifying to think of stars visible to the naked eye, such as Arcturus, as silent night-sky witnesses of the merging history of the Milky Way.

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